BELLCOMM, INC.
1100 Seventeenth Street, N.W. Washington, D.C. 20036

SUBJECT: The Effect of Venting and Leakage on AAP Cluster Attitude Control Propellant Requirements
Case 620

DATE: October 17, 1967

FROM: P. G. Smith

ABSTRACT

A certain amount of RCS propellant is needed to counteract the propulsive effects of leakage and venting from the AAP Cluster. Propellant requirements are determined for compensating for the moments produced by the fuel cell water vent and by general leakage of the O_2 - N_2 atmosphere for each of three Cluster configurations. The propellant requirements associated with leakage from a micrometeoroid penetration are also considered.

With the assumptions that all water produced by the fuel cells passes through the urine dump nozzle, and that an Auxiliary Attitude Control System located on the aft skirt of the S-IVB is used to counteract the disturbances, the maximum propellant requirements due to venting are 15 lb on the 28-day Mission A and 29 lb on Mission B, which lasts 56 days. A conservative set of assumptions regarding the nature of the atmospheric leakage yields 85 lb and 183 lb propellant requirements for the respective missions. Actual propellant requirements are expected to be lower.

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MEMORANDUM FOR FILE

1.0 INTRODUCTION

Discharge of material from the AAP Cluster causes a propulsive effect which can change the attitude of the vehicle. As the Auxiliary Attitude Control System (AACS) is used to correct attitude errors,* it is desired to know how much AACS propellant is required to counter the discharge propulsive effect, and it is the purpose of this memorandum to determine worst case estimates of these propellant requirements for several types of discharge.

Significant discharge propulsion may be produced by the venting of water produced by the fuel cells, by leakage of the O_2 - N_2 vehicle atmosphere through a hole caused by meteoroid penetration, or by O_2 - N_2 leakage other than through a meteoroid hole.

The problem of fuel cell venting propulsion has been studied by North American Aviation (Reference 1). The analysis is performed here anew, however, because the vehicle mass properties have changed significantly, additional Cluster configurations are of interest, and the AACS is used for countering the disturbance torques rather than the Service Module RCS jets used previously. Also, the North American study treated only emission from the Command Module (CM) steam vent, but it is expected that venting of water during the AAP missions will normally be via the urine dump nozzle instead.

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*Control moment Gyroscopes (CMG's) are used for attitude control on Mission B; however, this is of little importance here because CMG's are essentially storage devices, and the AACS is (unless a scheme for gravity-gradient "momentum dumping" is used) ultimately required to reinitialize the CMG's.

2.0 SPACECRAFT CONFIGURATIONS CONSIDERED

For Mission A, the AAP Cluster consists of an S-IVB Workshop, Airlock Module (AM), Multiple Docking Adapter (MDA), and a Command and Service Module (CSM). Two configurations are considered, namely those in which the CSM is docked on ports 4 and 5 of the MDA (the latter is shown in Figure 1). The CSM roll orientation relative to the MDA is arbitrary, subject, however, to certain constraints; for example, Sector 4 of the Service Module, which houses the fuel cells, must not be on the sunlit side of the spacecraft.

One configuration is considered for Mission B, that in which the CSM is docked on port 5 and the Lunar Module/ Apollo Telescope Mount (LM/ATM) is docked on port 1.

3.0 FUEL CELL WATER VENTING

3.1 Venting Moments

The Command Module steam vent is located near the base of the conical outer surface of the module. Specifically, if $\underline{n}_x$, $\underline{n}_y$, and $\underline{n}_z$ are unit vectors parallel to the right hand xyz axes shown in Figure 1, the location of the vent is (Reference 1, p.73).

$$\underline{r} = 73 \sin (\phi + 27.5°)\underline{n}_x + 153\ \underline{n}_y - 73 \cos (\phi + 27.5°)\underline{n}_z$$

inches when the CSM is docked on port 4. The roll angle, ϕ, of the CSM is zero when the CM windows are centered on the +x axis. When the CSM is docked on port 5

$$\underline{r} = 177\ \underline{n}_x - 73 \sin (\phi + 27.5°)\underline{n}_y - 73 \cos (\phi + 27.5°)\underline{n}_z$$

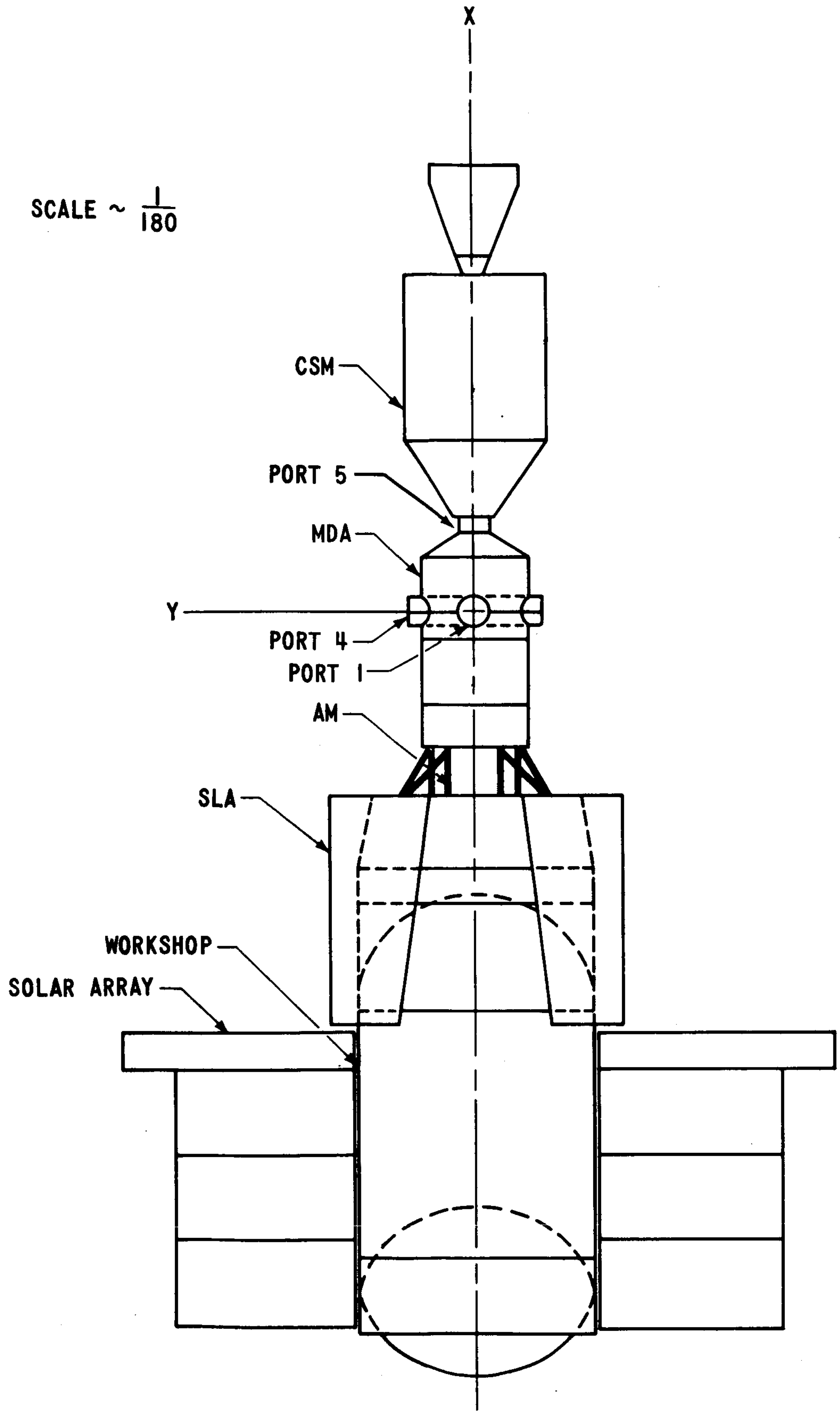

FIGURE 1 - MISSION A CLUSTER WITH CSM DOCKED ON PORT 5

inches, and in this instance ϕ vanishes when the CM windows are centered on the -y axis.

When discharge takes place via the steam vent, the thrust is

$$\underline{F} = \dot{w}\, I\, \underline{n}$$

in which $\dot{w}$ is the weight flow rate of the water, I is the specific impulse, which has a value of 70.3 sec (see Appendix), and $\underline{n}$ is a unit vector which has the value

$$\underline{n} = -.843 \sin(\phi + 27.5°)\underline{n}_x + .537\ \underline{n}_y + .843 \cos(\phi + 27.5°)\underline{n}_z$$

for docking on port 4 and

$$\underline{n} = .537 + .843 \sin(\phi + 27.5°)\underline{n}_y + .843 \cos(\phi + 27.5°)\underline{n}_z$$

for docking on port 5. A value of 4.0×10^{-4} lb/sec is obtained for $\dot{w}$ by assuming a 1.8 kw average power consumption; it is also assumed that all of the water produced by the fuel cells eventually passes through the vent.

The water produced may either be boiled in the glycol evaporators and thus leave the vehicle via the steam vent just discussed, or, if evaporative cooling is not needed, it will pass out through the urine dump nozzle as a liquid.* Calculations show that AAP-1/AAP-4 will need little cooling, and it is therefore not expected that the glycol evaporators and the steam vent will be used appreciably during these missions.

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*Tests of the urine dump nozzle in a vacuum chamber indicate that the water does leave the nozzle as a liquid (Reference 2).

The urine dump nozzle is located only about one foot from the steam vent, and checks on the calculations performed on the following pages show that the expressions for $\underline{r}$ and $\underline{n}$ just given for the steam vent are also sufficiently accurate for the urine dump nozzle. The magnitude of the thrust, however, is significantly different for the two means of discharge (see Appendix for urine dump nozzle thrust calculations).

The moment exerted on the vehicle by the venting thrust is

$$\underline{M} = (\underline{r} - \underline{r}_{mc}) \times \underline{F}$$

where $\underline{r}_{mc}$ is the position vector of the vehicle mass center.* It is assumed that this moment is nullified by firing the AACS jets continuously at a low thrust level. Actually, these jets fire intermittently at full thrust, but it may be shown that the amount of propellant required is the same in either case, provided that the jets are fired often enough so that the vehicle attitude excursions remain small. In Mission B, attitude control is achieved through Control Moment Gyroscopes, but the amount of propellant required for the periodic re-initialization of the gyroscopes is the same as that required for continuous nullification of any nonperiodic disturbance torques.

3.2 Countering Moments

The location and number of AACS jets has not yet been determined, so for the purposes of this report, we will assume that there are three pairs (a pair being two jets which produce oppositely-directed thrusts along a common line of action) of jets placed in what appear to be optimal locations so far as propellent consumption is concerned. Given the location of the

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*$\underline{r}_{mc}$ may be obtained from Reference 3 for the Mission A configurations; the same type of computation for Mission B yields the value (-109.5, -1.8, 56.1), in inches.

jet pairs, the thrusts F_1, F_2, and F_3 at which each pair must fire in order to nullify the disturbance torque may be computed from the three scalar simulataneous equations equivalent to the vector equation

$$\sum_{i=1}^{3} (\underline{r}_i - \underline{r}_{mc}) \times \underline{n}_i \, F_i = \underline{M}$$

where $\underline{r}_i$ is the position vector of pair i and $\underline{n}_i$ is a unit vector parallel to the force exerted by pair i. These computed thrusts are related to the required propellant weight, W, as follows:

$$W = \left(|F_1| + |F_2| + |F_3| \right) \frac{3600 \cdot 24 \cdot 28}{I_{sp}}$$

in which the propellant specific impulse I_{sp} has a value of 270 sec. This formula applies to a 28-day mission; values obtained from it must be doubled for the 56-day mission.

For Mission A, two of the AACS jet pairs are assumed to be located on opposite sides of the aft skirt of the Workshop in the xy plane; these are directed parallel to the z axis. The third pair of jets is located on the aft skirt in the xy plane and directed parallel to the y axis. The vehicle is symmetric about the xz plane for Mission B, and so the jets are now assumed to be located on the aft skirt in this plane, two pairs of them on opposite sides of the Workshop and directed parallel to the y axis, and the third pair directed parallel to the x axis. Of course, the jets cannot be relocated between missions: one must, in reality, locate the jets in what appears to be the optimal location for Mission A or in what seems to be best for Mission B. If the jets are so located in an apparently optimal location for one mission, calculations show that propellant requirements for the non-optimal mission are about 20% higher than the values presented.

3.3 Results for Discharge from the Steam Vent

For the Port 4 Configuration there exists a value of ϕ for which the line of action of the venting thrust passes nearly through the mass center of the vehicle. Thus, there exists an optimal value of ϕ for which a relatively small amount of propellant is required to nullify the disturbance. This may be seen in Figure 2 in which W is plotted against ϕ for the case where all of the water is discharged as steam.

The vehicle is symmetric for the Port 5 Configuration. Hence, W, for the 28-day mission only varies from 143 to 195 lb depending on ϕ. W for the 56-day Mission B ranges from 216 to 357 lb.

3.4 Results for Discharge From the Urine Dump Nozzle

If all of the water produced is discharged via the urine dump nozzle, the propellant requirements are only 7.8% of the requirements just presented for steam (see Section 3.1 and the Appendix). Thus, the maximum requirement for Mission A is 15 lb and the value for Mission B is 29 lb.

4.0 LEAKAGE DUE TO METEOROID PENETRATION

Penetration of a pressurized portion of the Cluster by a micrometeoroid will result in a propulsive effect as the $O_2 - N_2$ atmosphere leaks out. Analysis of this situation is imprecise, however, because of the uncertainties involved. Due to the uncertainty in predicting penetrations and the possible disastrous consequences of a penetration, micrometeoroid protection has been installed on the spacecraft to reduce the probability of a penetration during a one year interval to a very low value. Nevertheless, it would be interesting to know the propulsive thrust due to leakage from a penetration. We are handicapped, however, because very little is known about what size particles are apt to penetrate the skin, and furthermore, little is known about the size of hole made by a given

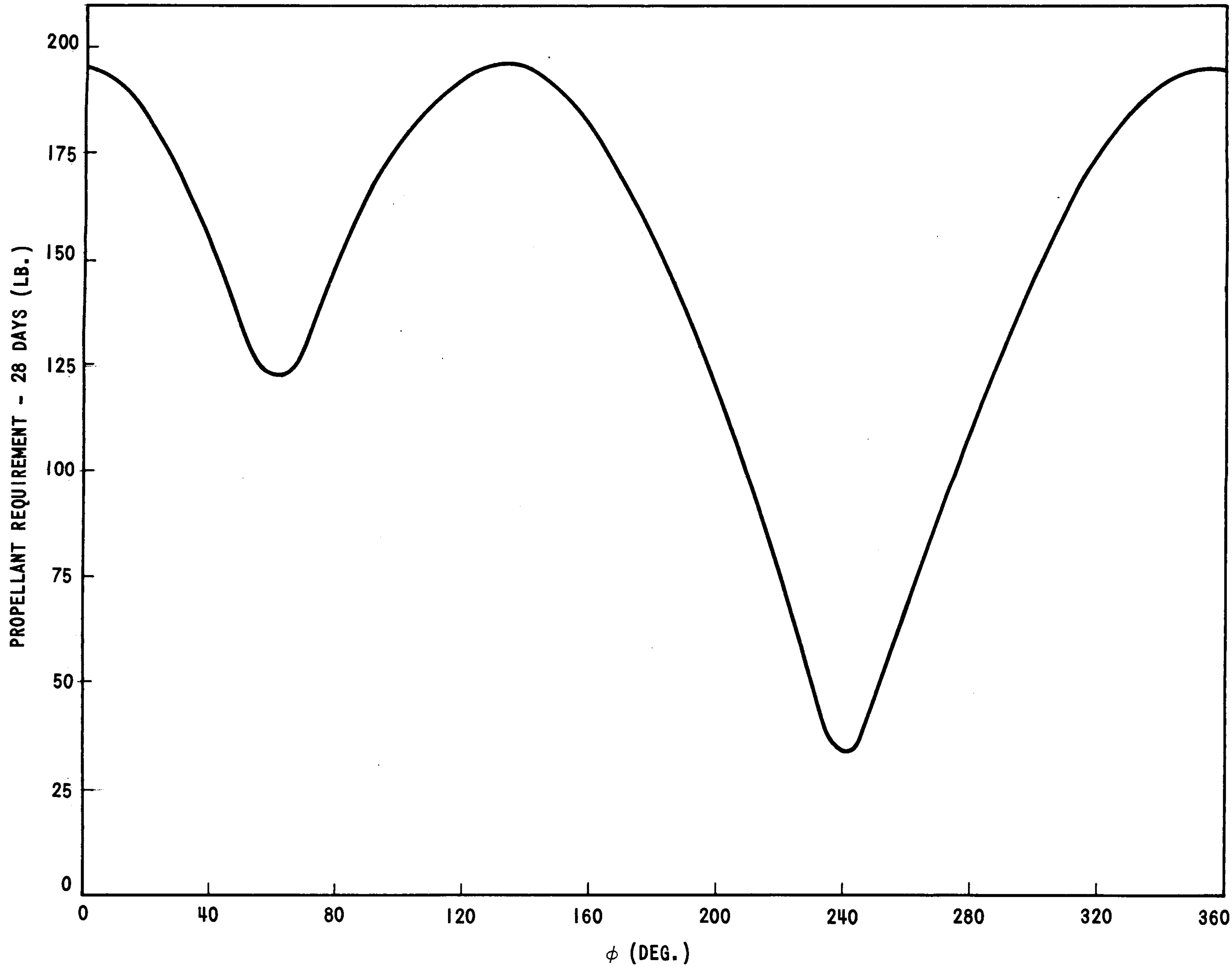

FIGURE 2 - PROPELLANT REQUIRED TO COUNTER STEAM VENTING IN PORT 4 CONFIGURATION

size particle. In view of these uncertainties it is assumed that the worst case penetration is one located at the aft end of the S-IVB H_2 tank and having a diameter of 0.0169 inch.

It is shown in the Appendix that this size hole corresponds to a flow rate of 4.8 lb/day, and it is probable that a larger hole will result in a shortened mission because of a proportionate increase in the consumption of propellant and O_2 - N_2.

Therefore, the analysis of leakage due to micrometeoroid penetration is treated in the next section simply as a leak at the rate of 4.8 lb/day located at the aft end of the H_2 tank.

5.0 THE PROPULSIVE EFFECT OF LEAKAGE

5.1 Assumptions

There are also uncertainites involved in assessing the mode of other types of leakage, and for this reason, assumptions must be made regarding the locations, directions, and magnitudes of the leaks. For purposes of sizing consumables, a maximum leakage rate of 4.8 lb/day has been assigned to each module.* It is assumed that for each module, 4.8 lb/day leaks out of one hole in the module which is located and directed so as to produce the largest disturbing moment. These assumptions are thought to be highly conservative: one engineer (Reference 4) at McDonnell-Douglas, who is working on leakage from the Workshop, feels that 0.5 lb/day is more realistic and that this will leak from several places rather than just one worst case location. Also, if leakage occurs in several places, it is apt to be largely self-equilibriating. These comments notwithstanding, the more conservative assumptions are used here because they yield worst case estimates and less conservative sets of assumptions seem to be highly arbitrary.

Disturbance torques are computed as before, using the value of specific impulse obtained in the Appendix, and the propellant required is computed as in Section 3.2.

5.2 Results

Including micrometeoroid penetration, thirteen modes of leakage are investigated. They are:

1. Mission A, Port 4 Configuration (28 days)

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*Exceptions are the AM, which has been allowed 1.0 lb/day and hard-docked interfaces, which are allowed 2.4 lb/day each.

a. CSM: Leak located on the conical surface of CSM at its base and in the yz plane; directed normal to the surface.

b. MDA: Center of Port 1; directed parallel to the z axis.

c. Workshop: Leakage from fill and drain line, which pierces the skin normally at x = -781" and 59.5° from the +z to the -y axis.

d. Meteoroid: Aft end of H_2 tank in xz plane and directed parallel to the z axis.

2. Mission A, Port 5 Configuration (28 days)

a. CSM: Base of CM in the xz plane and directed parallel to the z axis.

b. MDA: Same as 1b.

C. Workshop: Same as 1c.

d. Meteoroid: Same as 1d.

3. Mission B (56 days)

a. CSM: Base of CM in the xy plane; directed parallel to the y axis.

b. MDA: Center of Port 4; directed parallel to the y axis.

c. Workshop: Same as 1c.

d. Meteoroid: Aft end of H_2 tank in the xy plane; directed parallel to the y axis.

e. LM: Intersection of LM-ATM interface and the yz plane; directed parallel to the y axis.

The weight (pounds) of propellant required to nullify the moments produced by these modes of leakage for the duration of the mission are given in the following table.

Mode	W
1a	21.6
1b	27.9
1c	35.7
1d	25.5
2a	16.0
2b	7.9
2c	35.9
2d	25.8
3a	32.6
3b	26.4
3c	72.1
3d	51.8
3e	51.4

6.0 CONCLUSIONS

The propulsive effect of water from the CSM fuel cells being vented creates a disturbance moment which on Mission A requires at most 195 lb of propellant for its nullification if the water leaves via the steam vent and 15 lb at most if it leaves via the urine dump nozzle.* Corresponding requirements for Mission B are 357 lb and 29 lb. For the Mission A Port 4 Configuration the propellant required may be reduced substantially (38 lb for the steam vent and 3 lb for the urine dump nozzle) for some roll orientations of the CSM as it docks on the MDA.

*It is not expected that the steam vent will be used appreciably on the AAP Cluster missions.

Methods have been suggested for eliminating the venting propulsion problem altogether. North American has proposed (Reference 5) placing a "T" in the urine dump tube at the exit, thus making it nonpropulsive; this concept is now part of the baseline configuration. The possibility of storing all of the water produced for use as radiation shielding is also being considered.

Precise propellant requirements for offsetting the propulsive effect of leakage of the O_2 - N_2 atmosphere are unobtainable because the nature of the leakage is unknown. The highest propellant requirements result from leakage from the S-IVB fill and drain line, and a highly conservative set of assumptions relating to this mode of leakage leads to a requirement of 36 lb on Mission A and twice this amount on Mission B. By adding the leakage propellant requirements (see Table, Page 11) for all modules for each of the configurations, it can be shown that the propellant requirements for the entire Cluster may run as high as 85 lb on Mission A and 183 lb on Mission B. However, as these values are based on the additional conservative assumption that the propellant requirements are additive, one would probably expect the propellant requirements for the Cluster to be much lower than those given.

All of the propellant requirements given above are based on the assumption that the AACS jets are located on the aft skirt of the Workshop. If they are instead located on the Instrument Unit, as has also been suggested, then the amount of propellant required is expected to increase substantially.

On Mission B it may be possible to reinitialize the CMG's by use of the gravity-gradient torque rather than the AACS. With this scheme it is probable that no propellant will be required to counteract the effects of leakage and venting on this mission.

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Attachments
Appendix
References

APPENDIX

Formulas for Thrust and Flow Rate for Leakage into a Vacuum

The thrust, F, exerted on a vessel in a vacuum and which has an efflux but no influx of mass is

$$F = \dot{m} V_e + A_e p_e \tag{1}$$

where $\dot{m}$ is the mass flow rate, V is the flow speed relative to the vessel, A is the cross-sectional area of the flow, and p is the pressure of the medium; the subscript e refers to conditions at the exit plane. If the medium is in the gaseous phase at exit, one may assume that it behaves essentially as an ideal gas and make use of the equation of state:

$$p_e = \rho_e g R T_e \tag{2}$$

in which ρ and T are, respectively, the density and temperature of the gas, g is the acceleration of gravity, and R is the gas constant, a quantity which depends on the moecular weight, W_m, of the gas:

$$R = \frac{1544}{W_m} \frac{\text{ft lb}}{\text{lb } ^\circ\text{R}} \tag{3}$$

Now, ρ_e may be expressed in terms of variables already introduced by means of the continuity relationship

$$\rho_e = \frac{\dot{m}}{A_e \; V_e} \tag{4}$$

Substitution of equations (2) and (4) into (1) yields a more useful expression for thrust:

$$F = \dot{m} \left(V_e + \frac{g \; R \; T_e}{V_e} \right) \tag{5}$$

Specific impulse, I, is defined by means of the equation

$$F = \dot{w} \; I \tag{6}$$

where $\dot{w} = \dot{m}$ **g**. In the case at hand,

$$I = \frac{V_e}{g} + \frac{R \; T_e}{V_e} \tag{7}$$

There exists an exit speed for which I is minimal, and this is obtained from

$$\frac{dI}{dV_e} = \frac{1}{g} - \frac{R\ T_e}{V_e^{\ 2}} = 0 \tag{8}$$

which gives

$$V_e = \sqrt{g\ R\ T_e} = \frac{c_e}{\sqrt{\gamma}} \tag{9}$$

$$I_{min} = \frac{2c_e}{g\sqrt{\gamma}} \tag{10}$$

where c_e is the speed of sound for the gas at exit conditions, and $\gamma = c_p/c_v$ is the specific heat ratio. The exit Mach number, M_e, is defined as

$$M_e = \frac{V_e}{c_e} \tag{11}$$

Use of equation (11) in (7) yields

$$I = \frac{c_e}{g} \left(M_e + \frac{1}{\gamma M_e} \right) \tag{12}$$

Application to Steam

For water vapor

$$R = 85.8 \frac{\text{ft lb}}{\text{lb }^\circ\text{R}} \quad , \gamma = 1.28$$

and the speed of sound, obtained from

$$c_e = \sqrt{\gamma g \; R \; T_e} \tag{13}$$

is

$$\begin{array}{llll} 1218 \text{ ft/sec} & @ & T_e & = -40^\circ F \\ 1274 \quad '' & '' & '' & \quad 0^\circ F \\ 1329 \quad '' & '' & '' & \quad 40^\circ F \end{array}$$

Substitution of these values in equation (10) gives

$$\begin{array}{lllll} I_{min} = & 66.8 \text{ sec} & @ & T_e & = -40^\circ F \\ & 69.8 \quad '' & '' & '' & \quad 0^\circ F \\ & 72.8 \quad '' & '' & '' & \quad 40^\circ F \end{array}$$

To obtain a precise value for the specific impulse, it is necessary to have more information regarding the exit speed and temperature. In lack of such information, we will make some assumptions, the impact of which will then be discussed. The assumptions are

$$M_e = 1.0 \quad , \quad T_e = 0°F$$

These values are thought to be realistic: The Mach number at the exit of a converging nozzle is unity; it may be slightly less than unity due to losses or slightly greater if the flow is diverging at the exit plane. The ambient spacecraft temperature is about 70°F; T_e will be less than this due to expansion and evaporation, but, because of heat transfer in the plumbing, probably not too much less.

Nevertheless, these two parameters are not critical as far as the thrust is concerned. It may be seen from the values of I_{min} that the thrust will change by only about 10% for a temperature change of 80F°. Also, from Figure 3, the thrust will differ from the Mach-one value by only about 5% for Mach numbers of 0.8 - 1.2, the expected range of values. Thus, for $M_e = 1.0$ and $T_e = 0°F$,

$$I = \frac{1 + 1/\gamma}{2/\sqrt{\gamma}} \, 69.8 = 70.3 \text{ sec}$$

The possibility that the water is not gaseous at the exit plane must now be examined. First assume that it is indeed a vapor. From equations (2) and (4),

$$P_e = \frac{R\, T_e \dot{w}}{A_e\, V_e} \tag{14}$$

As previously discussed, a power consumption of 1.8 kw results in a weight flow rate of 4×10^{-4} lb/sec; and an exit orifice 2 1/2 in. in diameter has an area of .0341 ft^2. At the assumed exit conditions of 0°F and Mach one, equation (14) yields a

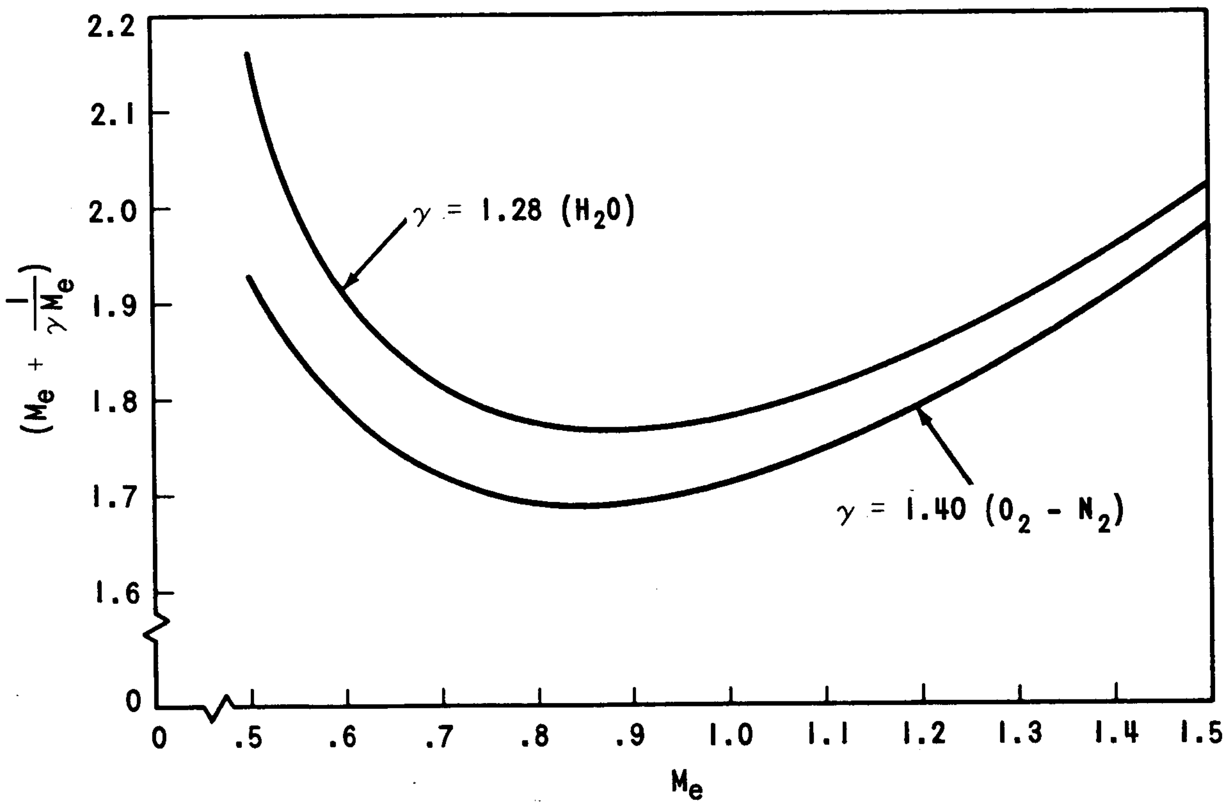

FIGURE 3 - THE VARIATION OF SPECIFIC IMPULSE WITH MACH NUMBER

pressure of .087 mm Hg, whereas the vapor pressure at this temperature is 1.0 mm Hg (Reference 6). Hence, the medium is well within the vapor phase at exit, and equation (2) may be assumed to be sufficiently accurate. Furthermore, even at Mach one and temperatures as low as -37°F, it may be shown that the pressure computed from equation (14) is less than the vapor pressure of water at this temperature.

Application to an O_2-N_2 Atmosphere

The AAP spacecraft will contain an atmosphere composed of oxygen at a partial pressure of 3.7 psia and nitrogen at a partial pressure of 1.3 psia. The constants associated with this mixture are

$$R = 50.1 \frac{\text{ft lb}}{\text{lb } {}^\circ\text{R}} \quad , \quad \gamma = 1.4$$

Isentropic expansion of the gas from rest inside the vehicle to Mach one at exit results in a change in temperature from 70°F inside to -18°F at exit (Reference 7). Since the gas will in fact acquire some heat from its surroundings while leaking out, the exit temperature may be expected to be above -18°F; thus, we will again make the assumptions

$$M_e = 1.0 \quad , \quad T_e = 0^\circ\text{F}$$

which in this case lead to

$$I = 54.3 \text{ sec.}$$

As before, it may be shown that M_e and T_e have little effect on the thrust.

Thrust Produced by Liquid Water

The above material does not apply to liquids, and it is thus necessary to compute the thrust produced at the urine dump nozzle by using equation (1) directly. The nozzle is designed to have a flow capability of 1.25 lb/min when the pressure at the nozzle entrance is 45 psia; the nozzle converges, having an exit diameter of .055 in. Equation (4) is used to obtain V_e = 20.3 ft/sec, and application of the Bernoulli equation to flow in the nozzle gives p_e = 42 psia. From equation (1)

$$F = .1136 \text{ lb}$$

Now, the flow capability of the nozzle is higher than the water production rate, so the average thrust for the mission, assuming the water to be discharged intermittently at the maximum rate, is

$$F = \frac{1.44 \text{ lb/hr}}{1.25 \times 60 \text{ lb/hr}} \times .1136 = 2.18 \times 10^{-3} \text{ lb}$$

This is only 7.8% of the thrust produced by a like amount of water when it passes through the evaporators and steam vent, and F is smaller still if discharge is at less than the maximum rate for a correspondingly longer period.

Relationship Between Flow Rate and Hole Size

It is desired to know what size round hole is required for a flow rate of 4.8 lb/day from a vessel containing and O_2 - N_2 atmosphere at 5 psia. From equation (4)

$$\dot{w} = g \, \rho_e \, A_e V_e \tag{15}$$

and from equation (2)

$$\rho_o = \frac{p_o}{g\ R\ T_o} \tag{16}$$

where the subscript refers to conditions inside the vessel for which $V_o = 0$. When $p_o = 5$ psia and $T_o = 70°F$, one obtains $\rho_o = 8.43 \times 10^{-4}$ slug ft^{-3}. Assuming isentropic expansion to $M_e = 1$, we have from Reference 7

$$\rho_e = 5.43 \times 10^{-4} \text{ slug ft}^{-3}\ ,\ T_e = -18°F$$

$$V_e = \sqrt{\gamma g\ R\ T_e} = 998 \text{ ft/sec}$$

Substitution of these values into equation (15) yields the value $A_e = 3.23 \times 10^{-6}$ ft^2. Hence, a hole .0169 in. in diameter produces a flow rate of 4.8 lb/day.

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